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Analysis of results on improved welded joints

by I. Huther, H.P. Lieurade, R. Souissi, A. Nussbaumer, B. Chabrolin and J.J. Janosch (France)

Abstract

Recent studies have shown that the use of improvement techniques on welds allows an increase in the level of admissible fatigue strength (even more than 100%). The aim of this study was to collect and validate literature data, create a data base containing the joint characteristics and fatigue results, make a statistical analysis of the data in order to quantify the effect of parameters influencing the fatigue strength and propose new S–N curves which are compared to those given in Eurocode 3. Four improvement techniques (grinding, TIG dressing, hammer peening, shot peening) and four joint types (butt, T joints, cruciform and longitudinal joints) were taken into account. Joint thicknesses less than 25 mm loaded in air with a stress ratio R between 0 and 0.1 were selected. Three classes of yield strength for the base metal were considered, <400, 400–600, >600. All S–N curves were above those of as-welded assemblies. The best results were obtained with hammer peening. The larger increase in the fatigue strength due to the use of improvement techniques was due to the occurrence of an initiation phase in addition to the crack propagation phase. During the initiation phase, the extension of existing crack-like defects is slowed down or even stopped. The duration of this phase increases with the total fatigue life.

Keywords: *Fatigue strength; TIG remelting; Hammers; Peening; Grinding; GTA welding; Statistical methods; Butt joints; Cruciform joints; T joints; Longitudinal welds; Crack initiation; Improvement techniques*

Résumé

Des études récentes ont montré que l'utilisation de techniques de parachèvement des soudures permettent d'accroître la résistance admissible à la fatigue (jusqu'à plus de 100%). Le but de cette étude est de compiler et de valider les données de la littérature, de créer une base de données indiquant les caractéristiques des joints et leur résistance à la fatigue, d'effectuer une analyse statistique des données a fin de quantifier l'influence des paramètres influant sur la résistance à la fatigue et de proposer de nouvelles courbes S–N qui sont comparées à celles spécifiées dans l'Eurocode 3. Quatre techniques d'amélioration (meulage, refusion TIG, martelage et grenaillage) et quatre types de joints (bout à bout, assemblages en T, assemblage en croix et joints longitudinaux) ont été pris en compte. Les épaisseurs considérées sont inférieures à 25 mm (sollicitations à l'air ambiant) et le rapport de charge R est de 0 et 0.1. Trois classes de limites d'élasticité ont été considérées: <400, 400–600 et >600 MPa. Toutes les courbes S–N étaient supérieures à celles des assemblages brut de soudage. Les meilleurs résultats ont été obtenus par martelage. L'augmentation de la résistance à la fatigue suite à ces traitements d'amélioration est due à l'apparition d'une phase d'initiation des fissures, en plus de la phase de propagation. Lors de la phase d'initiation, l'extension des fissures existantes est freinée et même stoppée. La durée de cette phase augmente avec la durée de vie totale en fatigue.

Mots clés: *Résistance a la fatigue; Refusion TIG; Marteau; Martelage; Meulage; Soudage TIG; Méthodes statistiques; Joints bout à bout; Joints cruciformes; Assemblages en T; Soudures longitudinales; Initiation des fissures; Méthodes d'amélioration*

IIS/IIW-1301-95 (ex doc. XIII-1691-95) Class A recommended for publication by IIW Commission XIII "Fatigue of welded components and structures" as the authors' own work.

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1. Introduction

Recent studies show that the use of improvement techniques on welds allows an increase in the level of the admissible fatigue strength (even of more than 100%). The gain is particularly good when these techniques are used with high tensile steel.

The utilization of research results in industry, to take advantage of these techniques during design, requires the following:

— the specification of each improvement technique, defining the operational and control practices.
— the modification of actual design codes concerning the fatigue of welded joints which do not take into account the improvement techniques and the efficiency of high strength steels.

The target of this study is to collect the literature data and to provide a statistical analysis.

The study includes the following steps:

— collection and validation of literature data
— creation of a data base in the form of sheets containing the joint characteristics and fatigue results
— statistical analysis of the data base to quantify the effect of the parameters influencing the fatigue strength
— from the statistical analysis, proposal of new S–N curves.

2. Improvement techniques

The standard improvement techniques selected in this study are the following:

— grinding of the weld toe to suppress defects and improve the shape of the weld toe
— TIG dressing to eliminate weld toe defects and to increase the weld toe radius
— hammer peening on the weld toe to modify the local geometry and introduce a compressive field of residual stresses

— shot peening to introduce a compressive field of residual stresses without modifying the geometry.

3. Data base

The data used in this study are bibliographical, from national and international conferences, publications, IIW documents, French IS and CETIM documents.

To analyse the results published in these documents, a standard data sheet was established from the data sheet used to collect laboratory fatigue results proposed by Commission XIII of the IIW [1]. This data sheet includes four principal parts (see Appendix 1):

- — chemical composition and mechanical properties of the base metal
- — welding process, composition and properties of the filler metal
- — characteristics of the improvement technique
- — characteristics of joints and fatigue test results.

For each type of improvement technique, the characteristics are:

- — for *grinding*: the type of grinding tool and its radius, the grinding direction, the number of passes and the ground depth
- — for *TIG dressing*: the current intensity, the voltage, the electrode diameter, the speed of dressing, the gas flux and its composition, and the number of passes
- — for *hammer peening*: the type of tool and its diameter, the pressure, the speed and the number of passes
- — for *shot peening*: Almen intensity, the tension, the type of balls and their diameter, the overlap ratio and the number of passes.

Particular attention is given to the joint geometry (micro and macro). But there is little information on this point.

Based on 62 references for TIG dressing and shot peening and 39 for grinding and hammer peening, the number of homogeneous series of test results on steel existing in the data base is:

— for grinding:	84
— for TIG dressing:	96
— for hammer peening:	33
— for shot peening:	53

plus the combinations:

- — stress release + TIG: 1 or
  TIG + stress release: 5
- — stress release + shot peening: 2 or
  shot peening + stress release: 2
- — TIG + shot peening: 2
- — stress release + grinding + shot peening: 1
- — hammer peening + grinding: 1
- — grinding + stress release: 1
- — grinding + shot peening: 1

plus the as-welded results to be used as reference (35).

Some 300 data sheets form the data base.

4. Parametric analysis

To analyse the content of the data sheets, data are grouped in the tables given in Appendix 2 versus improvement techniques and joint types with mention of the following parameters: yield strength, material, thickness, load condition, environment, stress ratio R and reference.

From these tables, for the four studied improvement techniques, we observe that:

- — the majority of data concerns butt joints, T joints, cruciform and longitudinal non-load-carrying joints (Fig. 1)
- — for a joint, there can exist different ranges of yield strength
- — for a type of joint, the range of thicknesses is large
- — fatigue testing in tension is predominant for the butt joints, cruciform and longitudinal non-load-carrying joints and in bending for T joints
- — the stress ratios R are essentially 0 and 0.1, there are few tests at $R = -1$
- — the tests are made in air essentially, few in sea water
- — for a given material, there are few test results from different origins
- — for a joint type and a material, there is, in most cases, only one thickness tested.

5. Statistical analysis of results

For all test results, whatever the improvement may be, the joint and the environment, the mean S–N curves were determined by a linear regression in log–log using S as function and N as variable.

If the population is homogeneous (little scatter), the linear regression in log–log using S as function is equivalent to the linear regression in log–log using N as function (used usually).

As the tests are heterogeneous (set of data different), to take S as variable leads to aberrant results, on the other hand, to take N as variable gives more coherent results.

These mean S–N curves are only used as guide to derive the slope corresponding to each improvement technique and type of joint.

5.1. *Preanalysis*

The statistical analysis was made on butt joints, T joints, cruciforms and longitudinal non-load-carrying joints in air, since the results are not sufficient in the other cases for a statistical analysis.

These results were grouped by improvement techniques, by type of joints, according the stress ratio R ($0 \leq R \leq 0.1/R = -1/R > 0.1/-1 < R < 0$), the yield strength (YS < 500 MPa/YS > 500 MPa), and the loading condition (tension and bending) in the tables given in Appendix 3.

From these tables, we observe that the majority of results are for $0 < R < 0.1$, and that there are few differences between the results in tension and those in bending.

5.2. *Analysis*

In the following, the study concerns butt welds, cruciform, T and longitudinal non-load-carrying fillet welds, in air, at R between 0 and 0.1, with thicknesses lower than 25 mm, and improved by one of the following improvement techniques: hammer peening, grinding, TIG dressing, and shot peening. We have considered three classes of yield strength of the base metal: YS < 400 MPa, 400 < YS < 600 MPa and YS > 600 MPa.

In each case, the test results were plotted using $\log \Delta\sigma$ versus $\log N$ ($\Delta\sigma$ stress range and N number of cycles at failure). The S–N curves were modelled by $\log N = -m \cdot \log \Delta\sigma + \log C$: the slope m, the constant $\log C$ and the standard deviation of $\log C$ were calculated (Appendix 4). We have plotted the slope m and the value of $\Delta\sigma$ at 2×10^6 cycles versus of the joint type for each

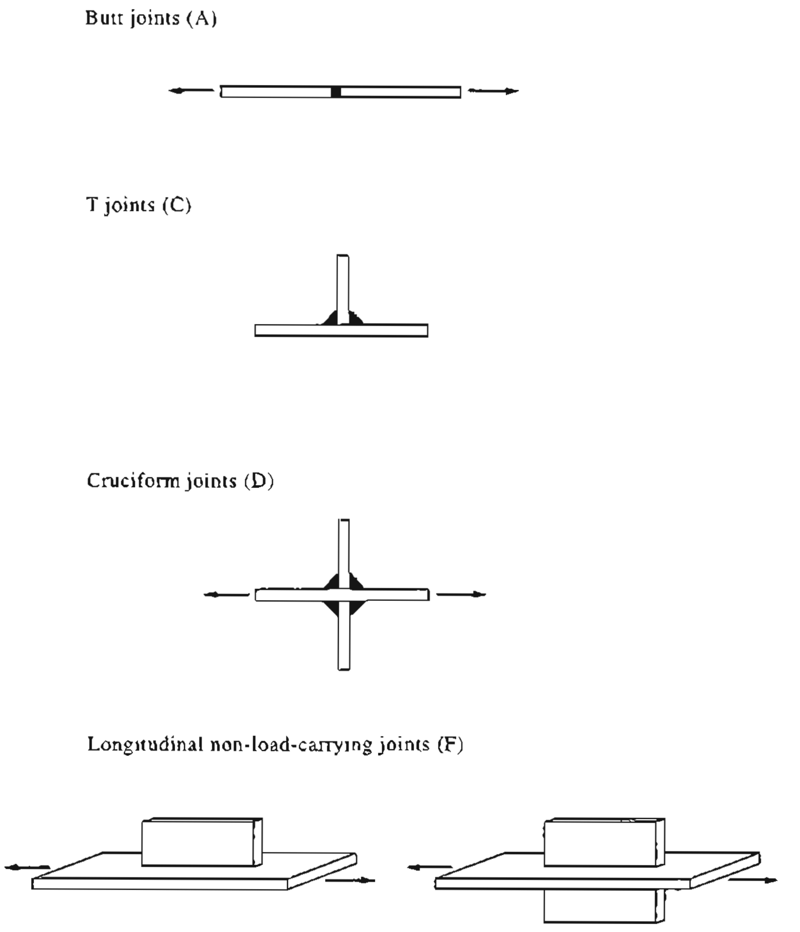


Fig. 1. Types of joints

improvement technique and yield strength classes of the base metal (Figs 2 and 4).

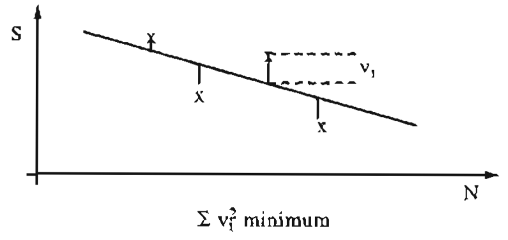
From histograms of m (Fig. 2), we observe that:

— the slope of the S–N curves varies according to the improvement technique for the same joint and according to the joint type for a given improvement technique

— the difference between the slopes can be important for the same type of joint according to the improvement technique (e.g. cruciform joints) or for the same improvement technique according to the joint type

— the slope varies for the same joint and the same improvement technique when the yield strength varies (e.g. ground cruciform joint).

Because of the scatter of results (differences due to plate thicknesses, welding process, and experimental conditions), we have determined empirically the envelope curves superior and inferior



Scheme 1

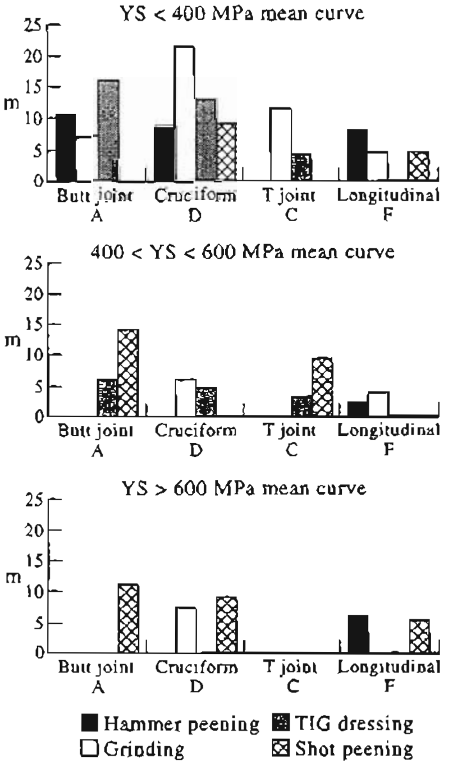


Fig. 2. Values of m deduced from mean curves (linear regression log $\Delta\sigma$ – log N)

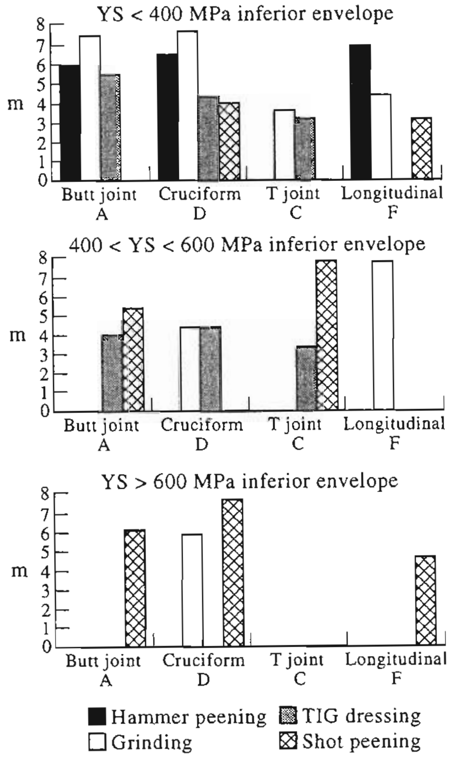


Fig. 3. Values of m deduced from inferior envelope curves (on coordinates log $\Delta\sigma$ – log N)

to the test results so that these curves crossed at 10^4 cycles. The tables of Appendix 4 give the estimated values of m, and $\Delta\sigma$ at 2×10^6 cycles corresponding to the inferior envelope curve, for each improvement technique and joint.

The histograms of m and $\Delta\sigma$ at 2×10^6 cycles as a function of the joint type for each improvement technique and yield strength

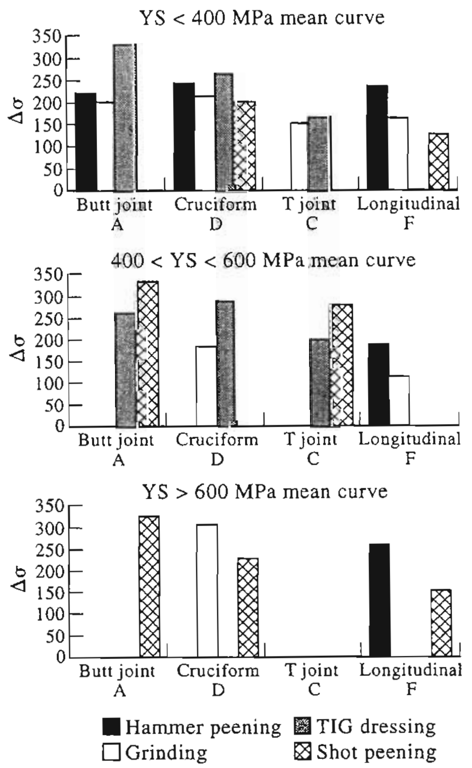


Fig. 4. Values of $\Delta\sigma$ achieved on regression curve (log $\Delta\sigma$ – log N) for 2×10^6 cycles

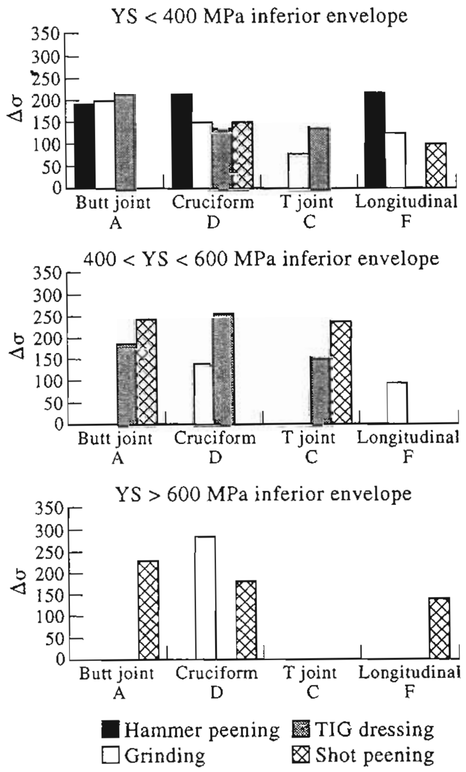


Fig. 5. Values of $\Delta\sigma$ deduced from inferior envelope curve (on coordinates log $\Delta\sigma$ –log N) for 2×10^6 cycles

Table 1. Slope of S–N curves

Slope m	Butt joint (A)	Cruciform (D)	T joint (C)	Longitudinal (F)
Grinding	7	7	7	5
Hammer peening	10	10	10	8
TIG dressing	7	6	4	—
Shot peening	9	9	9	5

were plotted (Figs 3, 5). We observe that the slopes are smaller than those achieved by linear regression, but vary in the same way.

6. Proposed S–N curves

From the results of the regression analysis, the following slopes were derived. The slopes are independent of the yield strength (YS) and all greater than 3 (Table 1).

The classification of the m values by increasing order is in relation to the efficiency of the improvement technique. In all cases, m is greater than as-welded joints where $m = 3$.

Determination of design S–N curves is based on a statistical evaluation according to Eurocode 3 Annex Z [2]. The slope is imposed at the value in Table 1, thus all results may be transformed in stress ranges at 2×10^6 cycles. The analysis provides the following results (Table 2):

- $\Delta\sigma_m$ mean stress range (50% of probability of failure for 2×10^6 (cycles)
- s standard deviation associated with $\Delta\sigma_m$ (assumed log-normal)
- S_k stress range for 2×10^6 cycles and 5% of probability of failure (this characteristic value is an estimation with a 75% level of confidence)

Table 2. Improvement results

YS	Joint	Techniques	spe nb	m	$\Delta\sigma_m$	s	S_k	S_{Rk}	S_{RL} (AW)	S_{Rk}/S_{RL} (AW)
< 400	Butt joint	Hammer peening	30	10	222	15	195	193	90	2.1
		TIG dressing	≈60	7	291	57	202	178		2.0
	Cruciform	Hammer peening	19	10	244	18	211	209	71	2.9
		TIG dressing	48	6	233	49	152	126		1.8
		Shot peening	66	9	196	28	150	144		2.0
	T joint	TIG dressing	25	4	164	20	127	124	71–90	1.7
	Longitudinal	Grinding	45	5	164	29	115	103	63–90	1.6
		Hammer peening	11	8	226	8	210	206		3.2
		Shot peening	26	5	123	15	97	95		1.5
400 <	Butt joint	TIG dressing	156	7	280	41	215	206	90	2.3
< 600	Cruciform	Grinding	25	7	195	17	164	162	71	2.3
		TIG dressing	154	6	273	58	182	155		2.2
	T joint	TIG dressing	74	4	213	45	143	122	71–90	1.7
		Shot peening	30	9	278	34	222	220		3.1
> 600	Butt joint	Shot peening	99	9	326	52	242	226	90	2.5
	Cruciform	Shot peening	33	9	232	40	163	146	71	2.0
	Longitudinal	Shot peening	18	5	148	14	122	121	63–90	1.9

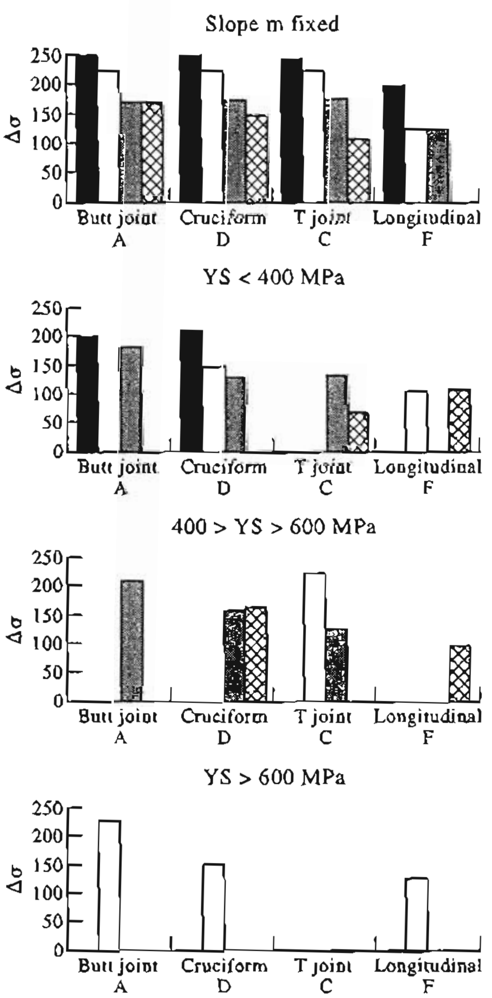


Fig. 6. Values of m fixed for characteristic curves log $\Delta\sigma$ – log N and corresponding levels of $\Delta\sigma$ (S_d) determined for 2×10^6 cycles

— S_d design stress range for 2×10^6 cycles. It is obtained by $S_d = \dfrac{S_k}{\gamma'_{Mf}}$ where γ'_{Mf} is a relevant safety factor determined to fulfil the required safety level (or safety index β)

— S_{Rk} modified characteristic value obtained by

$$S_{Rk} = S_d \cdot \gamma_{Mf} = S_k \frac{\gamma_{Mf}}{\gamma'_{Mf}}$$

, where γ_{Mf} is the safety factor imposed by Eurocode 3, while γ'_{Mf} has been determined by statistical analysis of test results. In that way, S_{Rk} is the final value that may be adopted for the detail classification tables.

— S_{RL} (AW) is corresponding class (stress range for 2×10^6 cycles) for as-welded detail of Eurocode 3.

The statistical analysis is based on the assumption of independence between the sample mean and the sample standard deviation, and on $\Delta\sigma$ (or N) being log-normal. It may then be shown that the probability of any quantity m–$k{\cdot}s$ (m sample mean, s sample standard deviation) being lower than a given level is calculated from a non-centred Student's distribution, the parameters of which depend on the number of available test results.

We have plotted the imposed m and the corresponding $\Delta\sigma$ determined for 2×10^6 cycles, versus joint types and improvement techniques for each class of yield strength. YS < 400, 400 < YS < 600, YS > 600 MPa (Fig. 6), and the S–N curves for each type of joint (Fig. 7).

From the S–N curves (Fig. 7), we observe that:

— All curves are above the Eurocode 3 curves corresponding to the as-welded joint, and exhibit a resistance increase due to improvement techniques.

— The S–N curves of improved joints in high tensile steel (YS > 400 MPa) are above or on those of improved joints in mild steel.

— For cruciform and longitudinal joints, the hammer peening gives the better results.

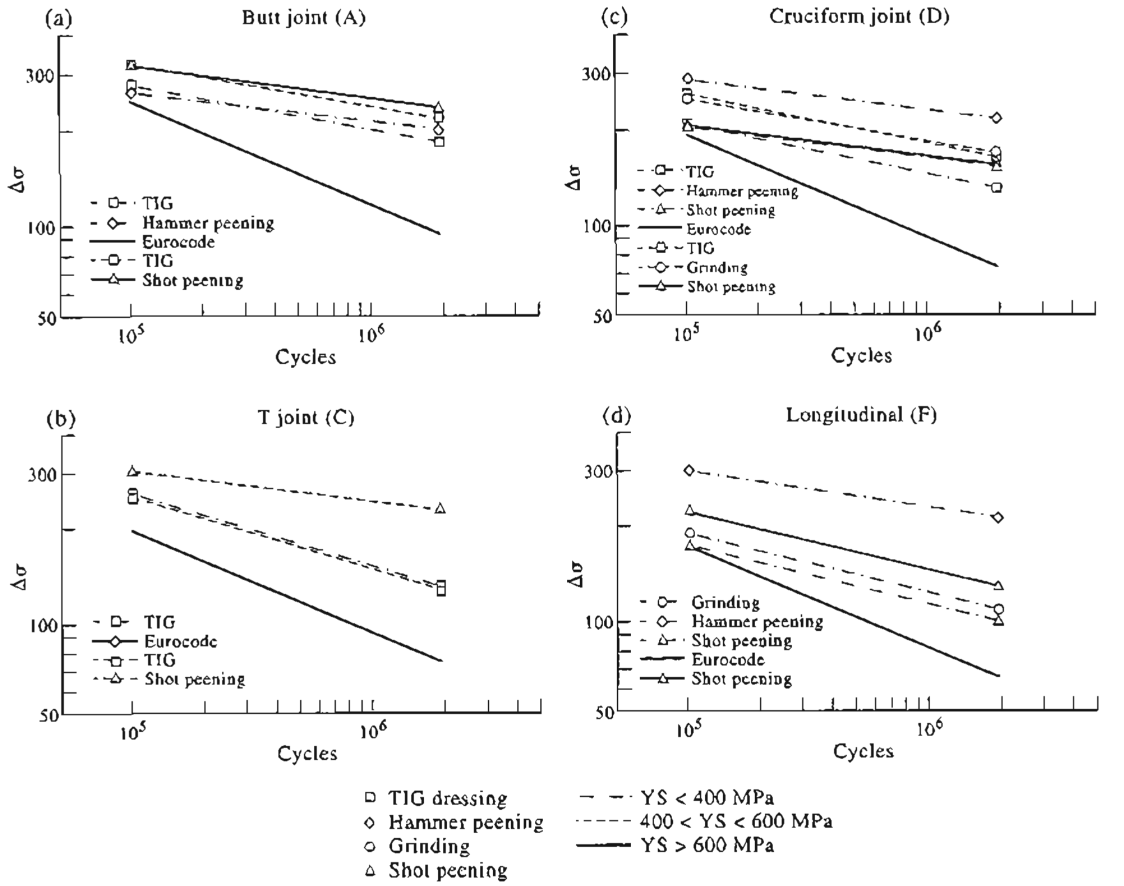


Fig. 7. Comparison between characteristic curves of Eurocode and those achieved in the case of improved joints for each joint type studied

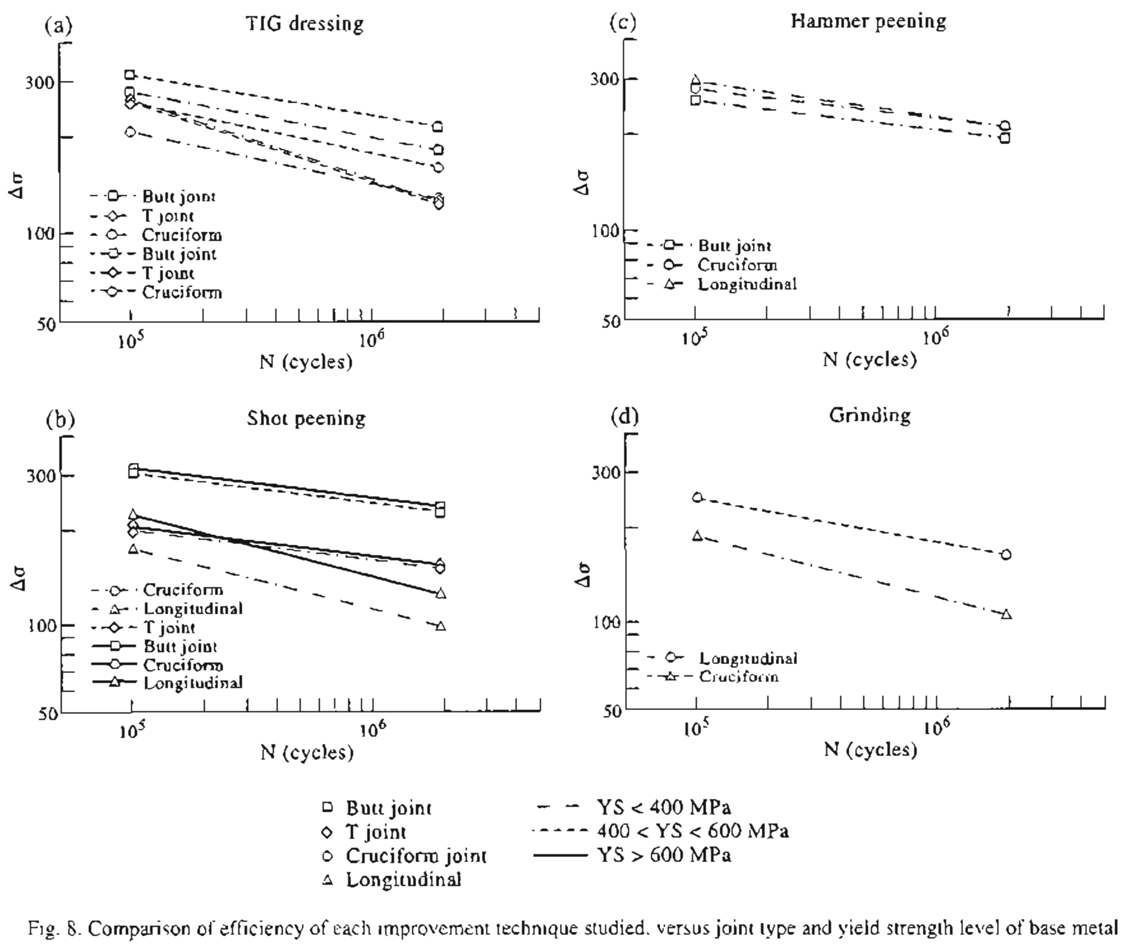


Fig. 8. Comparison of efficiency of each improvement technique studied, versus joint type and yield strength level of base metal

Table 3. As-welded results

Joint	spe nb	m	$\Delta\sigma_m$	s	S_k	S_{Rk} (this study)	S_{Rk} (Eurocode 3)
Butt joint	100	3	136	30	92	86	90
Cruciform	91	3	124	28	81	73	71
T joint	66	3	140	28	98	94	71–90
Longitudinal	18	3	85	9	68	68	63–90

Table 4.

Joint	Techniques	m	S_{Rk} Re < 400	S_{Rk} Re > 400	S_{Rk} (AW)
Butt joint	TIG dressing	7	180	205	90
	Shot peening	9		225	
	Hammer peening	10	195		
Cruciform	TIG dressing	6	125	155	71
	Grinding	7		160	
	Shot peening	9	145	145	
	Hammer peening	10	210		
T joint	TIG dressing	4	125	125	71–90
	Shot peening	9		220	
Longitudinal	Grinding	5		105	63–71–
	Shot peening	5	95	120	90
	Hammer peening	8	200		

m: slope of S–N curve

S_{Rk}, design stress range of improvement joints

S_{Rk} (AW): Eurocode 3 design stress range of as-welded joints

— For butt joints, and the same steel (mild or high tensile strength) whatever the improvement may be, the results are similar (the S–N curves merge).

The S–N curves versus the improvement techniques were plotted in Fig. 8.

We observe that:

— for TIG dressing and shot peening, the S–N curves are different according to the joint; the better results are achieved for butt joints and the worse for longitudinal joints, according to the code classification of as-welded joints;

— for hammer peening, the S–N curves of each joint are close;

— for grinding, a great difference exists between the results according to the joint type.

7. Comparison between as-welded results and Eurocode 3

For each publication of improved results, as-welded results are given as reference. These as-welded tests are analysed by the same method of tests as improvement joints (Annex Z of the Eurocode 3). A single class of yield strength are given because the yield strength has no influence on S–N curve.

The slope of the S–N curve is imposed at 3, as in Eurocode 3, and the results may be transformed in stress range at 2×10^6 cycles. The analysis provides the results shown in Table 3.

The as-welded S_{Rk} are similar to those of Eurocode 3, therefore the comparison between improvement results and those of Eurocode 3 is justified.

For the butt joints, the experimental S_{Rk} is lower than that of Eurocode 3, perhaps because the test specimens were indis-aligned. This phenomenon is not negligible. For T joints, the test value is nearer to 90 than 71 because the load of testing is bending and not tension. For the other joints, the S_{Rk} values are the same.

8. Conclusion

This study collected literature data in the form of standard data sheets (some 300 sheets), to analyse them statistically and to establish S–N curves.

Four improvement techniques (*grinding, TIG dressing, hammer peening, shot peening*) for four joints (*butt, T joints, cruciform,* and *longitudinal joints*) were taken into account in this study.

After a preliminary analysis, we selected joints with *thickness smaller* than *25 mm* loaded in air, with a stress ratio R, between 0 and 0.1. *Three classes of yield strength* of base metal (YS < 400, 400 < YS < 600, YS > 600 MPa) were considered.

After a statistical analysis (linear regression of test results), we have fixed the slopes of the S–N curves for each joint type and improvement techniques whatever the yield strength may be. *All* these *slopes* are *greater* than *3*. They were used to derive the design stress range S_{Rk} (Eurocode 3 method) at 2×10^6 cycles. *All* the *S–N curves* achieved are *above* those of *as-welded* assemblies. The better results are obtained with hammer peening.

In summary, we achieve the results shown in Table 4.

The rather large increase in the fatigue strength, due to the use of improvement techniques, can be explained by the occurrence of a so-called initiation phase in addition to the crack propagation phase. During the initiation phase, the extension of existing "crack-like" defects is slowed down or even stopped. The duration of this phase increases with the total fatigue life (or the decrease on the stress range). It explains the effect observed on the slope of the S–N curves.

References

1. Fatigue testing of welded components, *Welding in the World*, Vol. 29, No. 9/10, doc. IIS/IIW XIII-1090-90.

2. Eurocode 1, Annex Z: Informative determination of design resistance from tests, 1992.

Appendix 1

Standard data sheet

Fatigue data sheet on welded joints

Title:

Authors:

Reference:

Parent material:

Grade

Chemical composition (%)

Heat treatment

Mechanical properties

YS (MPa)	UTS (MPa)	E (%)	R.A.	KVC (J/cm^2)	

Endurance limit at cycles $R =$ $\Delta\sigma_D =$ MPa $s =$ MPa

Welding: Welding process Position

Electrode Flux Gas

Chemical composition of the filler material

Mechanical properties of the deposit material

YS	UTS	E	R.A.	KCV	

Pass n°	Electrode size	Intensity (A)	Tension (V)	Speed (cm/mn)	Plate preparation	Preheat temperature

Improvement:

Surface treatment after welding

Mechanical treatment after welding

Intensity	Tension					

Specimen:

Thickness: mm Width: mm Length: mm

Observations:

Fatigue testing conditions:

Test machine: $R =$ Temperature:
Loading mode: Frequency: Environment:
Wave form: σ_{mean}:
Nominal area:
Failure criterion:

Test results:

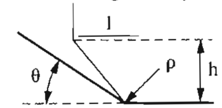
Ref: as welded $\Delta\sigma$ (2 x 10^6 cycles/50%) = MPa $s =$ MPa

$\Delta\sigma$(*) (MPa)	N (cycles)	Observations (**)

(*) DS = Nominal stress range
(**) F: Failed specimen (toe or root)
NF: Non failed at N cycles

$\boxed{\Delta\sigma \text{ (2 x } 10^6 \text{ cycles/50\%) = MPa} \quad s = \text{MPa}}$

Local geometry

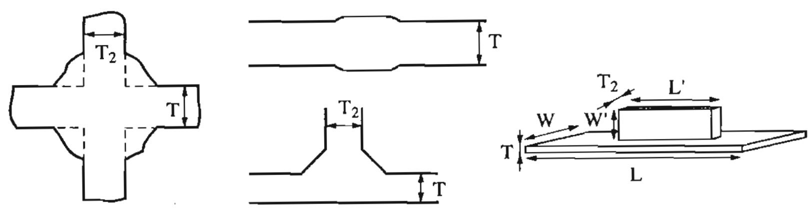


$\rho =$ mm $\theta =$ °
$l =$ mm $h =$ mm

Global geometry

$T =$ mm $T_2 =$ mm
$W' =$ mm $L' =$ mm

Type of joints:



Example of data sheet

Fatigue data sheet on welded joints

Title: Improvements of fatigue strength in fillet welded joint b, CO_2 soft plasma arc dressing on welded toe
Authors: W. Shimada, S. Hoshinouchi, S. Hiramoto, A. Hijikata, S. Yoshioka, A. Inoue
Reference: IIW-XIII-881-78

Parent material:

Grade HT 60

Chemical composition (%)

C	Si	Mn	P	S	Nb	Ni	Cr			
0.16	0.45	1.42	0.018	0.006	0.06	0.01	0.02			

Heat treatment

Mechanical properties

YS (MPa)	UTS (MPa)	E (%)	R.A.	KVC (J/cm^2)	
421	588	43			

Endurance limit at 10^7 cycles R = 0.1 $\Delta\sigma_D$ = MPa s = MPa

Welding: Welding process CO_2 semi-auto Position

Electrode Flux Gas CO_2

Chemical composition of the filler material

C	Si	Mn	P	S	Mo				
0.16	0.38	0.87	0.012	0.009	0.41				

Mechanical properties of the deposit material

YS	UTS	E	R.A.	KCV	
570	657	26			

Pass n°	Electrode size	Intensity (A)	Tension (V)	Speed (cm/mn)	Plate preparation	Preheat temperature
	Ø 1.2 mm	240	33	50		

Improvement:

Surface treatment after welding stress relieved at 625°C for 2h + TIG dressed

Mechanical treatment after welding

Intensity	Tension	Ø (mm)	Speed (cm/mn)	Gas flow		
250 A	14 V	3.2	14	Ar 10 l/mn		

Specimen:

Thickness: 25 mm Width: 75 mm Length: 825 mm

Observations:

Fatigue testing conditions:

Test machine: R = 0.1 Temperature:
Loading mode: 4 point bending Frequency: 30 Hz Environment: air
Wave form: σ_{mean}.
Nominal area:
Failure criterion: Crack initiation

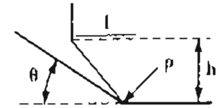
Test results:
Ref: as welded $\Delta\sigma$ (2 x 10^6 cycles/50%) = MPa s = MPa

$\Delta\sigma$(*) (MPa)	N (cycles)	Observations (**)
353	1.2 x 10^5	F
333	1.7 x 10^5	F
314	1.4 x 10^5	F
275	10^6	F
255	10^7	NF
235	10^7	NF

(*) DS = Nominal stress range
(**) F: Failed specimen (toe or root)
NF: Non failed at N cycles

$\Delta\sigma$ (2 x 10^6 cycles/50%) = MPa
s = MPa

Local geometry

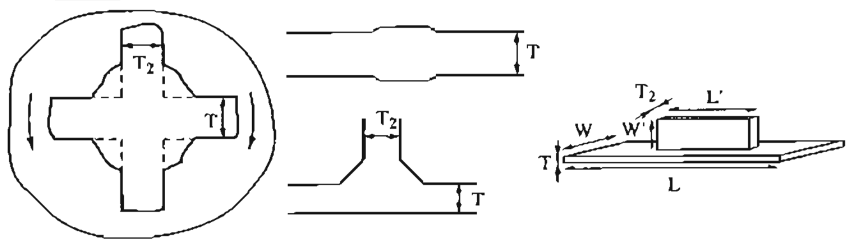


ρ = 5.85 mm θ = 42 °
l = mm h = mm

Global geometry

T = 25 mm T_2 = 25 mm
W' = mm L' = mm

Type of joints:



Appendix 2 Part 1: Recapitulative tables of the data base, grouping the test versus improvement techniques and joint types with mention of the following parameters: yield strength, material, thickness, load condition, environment, stress ratio

Material	YS (MPa)	Improvement	Type of joints	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	References
A42 FP	280	Mill grinding	Butt welded	10	Tension	−1	Air	23
A 5083P-0 (aluminium)		Toe grinding	Butt welded	6	Bending	−1	Air	15
		Laser remelting (speed 100 mm/mn) (V)	Butt welded	6	Bending	−1	Air	15
		Laser remelting (V = 100 mm/mn) (DFs = 2 mm)	Butt welded	6	Bending	−1	Air	15
		Laser remelting (V = 800 mm/mn)	Butt welded	6	Bending	−1	Air	15
		Laser remelting (V = 500 mm/mn) (DFs = 4 mm)	Butt welded	6	Bending	−1	Air	15
AE 235	233	Hammer peening	Butt welded	12	Bending	0	Air	38
AE 355	399	Hammer peening	Butt welded	12	Bending	0	Air	38
BS 15	250	Light grinding	Longitudinal	12.7	Tension	0	Air	3, 33, 35, 36
		Full grinding	Longitudinal	12.7	Tension	0	Air	3, 33, 35, 36
		Full grinding	Longitudinal	12.7	Tension	0	Air	3, 33, 35
		Light grinding	Cruciform	12.7	Tension	0	Air	3, 33, 34, 35, 36
		Full grinding	Cruciform	12.7	Tension	0	Air	3, 33, 35, 36
		Full grinding	Cruciform	12.7	Tension	0	Air	3, 33, 35
		Full grinding (full penetration welds)	Longitudinal	12.7	Tensile	0	Air	33, 35
		Hammer peening	Longitudinal	12.7	Tensile	0	Air	33, 35
		Hammer peening	Cruciform	12.7	Tensile	0	Air	33, 34, 35
		Hammer peening + full grinding	Cruciform	12.7	Tensile	0	Air	33, 35
BS 968	340	Light grinding	Cruciform	12.7	Tensile	0	Air	3, 33, 35
		Full grinding	Cruciform	12.7	Tensile	0	Air	33, 35
		Full grinding	Cruciform	12.7	Tensile	−1	Air	33, 35
		Full grinding	Longitudinal	12.7	Tensile	0	Air	33, 35
		Hammer peening	Cruciform	12.7	Tensile	0	Air	33, 35
BS 4360/43A	245	Disc ground	Cruciform	12.5	Tension	0	Air	3, 6, 38
		Disc ground	Cruciform	12.5	Tension	−1	Air	3, 5, 38
		Disc ground	Cruciform	12.5	Tension	0.5	Air	3, 5, 38
		Toe burr ground	Cruciform	12.5	Tension	0	Air	3, 6, 38
		Fully burr ground	Cruciform	12.5	Tension	0	Air	3, 6, 38
		Disc ground	Cruciform	12.5	Tension	0	Air	3, 5
		Hammer peening (4 passes)	Cruciform	12.5	Tension	0	Air	5, 18, 25
		Hammer peening (4 passes)	Cruciform	12.5	Tension	−1	Air	5, 18, 25, 28
		Hammer peening (4 passes)	Cruciform	12.5	Tension	0.5	Air	5, 18, 25, 28
		Hammer peening (1 pass)	Cruciform	12.5	Tension	0	Air	6, 18
		Hammer peening (2 passes)	Cruciform	12.5	Tension	0	Air	6, 18
		Hammer peening (3 passes)	Cruciform	12.5	Tension	0	Air	6, 18
		Hammer peening (4 passes)	Cruciform	12.5	Tension	0	Air	6, 18, 38
BS 4360/50A	333	Hammer peening (4 passes, Ø12)	Cruciform	13	Tension	0	Air	8
		Hammer peening (2 passes, Ø6)	Cruciform	13	Tension	0	Air	8
		Hammer peening (4 passes, Ø6)	Cruciform	13	Tension	0	Air	8
		Hammer peening (8 passes, Ø12)	Cruciform	13	Tension	0	Air	8
		Hammer peening (8 passes, Ø6)	Cruciform	13	Tension	0	Air	8

Appendix 2. Continued on next page

Appendix 2 Part I: Continued

Material	YS (MPa)	Improvement	Type of joints	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	References
EH 36	360	Shallow burr grinding + disc grinding	Cruciform	10	Tension	0.1	Air	51
			Cruciform	22	Tension	0.1	Air	51
			Cruciform	40	Tension	0.1	Air	51
			Cruciform	80	Tension	0.1	Air	51
			T	22	3-point bending	0.1	Air	51
			T	40	3-point bending	0.1	Air	51
			T	80	3-point bending	0.1	Air	51
		Toe grinding (burr) depth: 0.4	Cruciform	10	Tension	0.1	Air	51
			Cruciform	22	Tension	0.1	Air	51
			Cruciform	40	Tension	0.1	Air	51
			Cruciform	80	Tension	0.1	Air	51
			T	22	3-point bending	0.1	Air	51
			T	40	3-point bending	0.1	Air	51
			T	80	3-point bending	0.1	Air	51
F		Local explosive treatment	Butt welded	12	Bending	—	Air	14
Fe 510D or St 52-3	385	Multiple point peening	Longitudinal (gusset 100 mm)	20	Tension	0.1	Air	21–27
		Simple point peening	Longitudinal (gusset 100 mm)	20	Tension	0.1	Air	21–27
		Multiple point peening	Longitudinal (gusset 200 mm)	20	Tension	0.1	Air	21–27
		Simple point peening	Longitudinal (gusset 200 mm)	20	Tension	0.1	Air	21–27
H 75-3	810	Grinding	Butt welded	8		0	Air	20
HSLA	472	Burr grinding	Longitudinal	20	Tension	0.1	Air	9, 22
		Burr grinding	Reinforcement	20	Tension	0.1	Air	9, 22
		Hammer peening (single point)	Longitudinal	20	Tension	0.1	Air	9, 22
		Hammer peening (single point)	Reinforcement	20	Tension	0.1	Air	9, 22
		Hammer peening (multiple points)	Longitudinal	20	Tension	0.1	Air	9, 22
		Hammer peening (multiple points)	Reinforcement	20	Tension	0.1	Air	9, 22
HT 50	390	Ground	Butt welded	12.7	Tension	0	Air	3
		Ground	Butt welded	20	Tension	env. 0	Air	3
		Ground	Butt welded		Tension	0	Air	38
		Ground	Butt welded		Tension	0	Air	38
HT 60	420	Ground	Cruciform	25	Bending	env 0	Air	3
HT 80	785	Ground	Cruciform	25	Tension	0	Air	3
		Ground (MMA weld)	Butt welded	50	Bending	env. 0	Air	3
		Ground (submerged arc weld)	Butt welded	50	Bending	env. 0	Air	3
		Ground	Butt welded		Tension	0.05	Air	38
		Ground			Tension	0.6	Air	38
KE 36 (TMCP)	452–479	Ground	Cruciform (width 50 mm)	40	3-point bending	0	Air	12
		Ground						
		Ground (15 pass weld)	Cruciform (width 300 mm)	40	3-point bending	0	Air	12
		Ground (6 pass weld)						
			Cruciform	22	3-point bending	0	Air	12
			Cruciform	22	3-point bending	0	Air	12
Loycon QT	725	Ground	Cruciform	12.5	Tension	0	Air	3–31, 32, 35
		Hammer	Cruciform	12.7	Tensile	0	Air	32, 32, 35
SM 58 Q	556	Grinding (Ø6) grain 24	Cruciform	14	Tension	0	Air	1
		Grinding (Ø12) grain 24	Cruciform	14	Tension	0	Air	1
		Grinding (Ø6) grain 60	Cruciform	14	Tension	0	Air	1
		Grinding (Ø12) grain 60	Cruciform	14	Tension	0	Air	1
		Hammer peening (Ø3) 1 pass	Cruciform	14	Tension	0	Air	1

Appendix 2. Continued on next page

Appendix 2 Part 1: Continued

Material	YS (MPa)	Improvement	Type of joints	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	References
BS 4360/50B	400	Hammer peening (4 passes)	Cruciform	13	Tension	0	Air	8
		Hammer peening (4 passes) + spot heated (1 pass for weld)	Cruciform	13	Tension	0	Air	8
		Hammer peening (4 passes) + spot heated (2 passes for weld)	Cruciform	13	Tension	0	Air	8
BS 4360/50C		Grinding (depth 2.5 mm. full width)	T	12.5	Tensile	0	Air	30
		Grinding (depth 4.2 mm, full width)	T	12.5	Tensile	0	Air	30
		Grinding (depth 2.5 mm, full width)	Cruciform	12.5	Tensile	0	Air	30
		Grinding (depth 2.5 mm. partial width)	T	12.5	Tensile	0	Air	30
		Grinding (depth 4.2 mm, partial width)	T	12.5	Tensile	0	Air	30
		Grinding (depth 6.25 mm, partial width)	T	12.5	Tensile	0	Air	30
BS 4360/50D	345	Disc ground	Cruciform	38	Bending	0.1	Air	2, 3, 4, 17, 37, 38
		Grinding	Cruciform	38	Bending	0.1	Sea water	2, 38
		Disc ground	Cruciform	25	Tension	0	Air	2, 3, 38
		Disc ground	Cruciform	38	Bending	0	Precored cathodic protection	2, 4, 17, 37
		Disc ground	Cruciform	38	Bending	0	Cathodic protection	2
BS4360/50D	345	Grinding	T	30	Bending	0.05	Air	7
		Hammer peening	Cruciform	25	Tension	0	Air	2–38
		Hammer peening	Cruciform	38	Bending	0	Air	2, 4–38
		Hammer peening	Cruciform	38	Bending	0	Sea water with cathodic protection	2, 4
		Grinding	T	50	4-point bending	0	Air	24
		Grinding	T	100	4-point bending	0	Air	24
BS 4360/50E	379	Grinding (burr) after precracking	Pipe	16	Bending	−1	Air	29, 39
		Grinding (burr) after repair weld 50%	Pipe	16	Bending	−1	Air	28, 29
		Grinding (burr) repair weld 100%	Pipe	16	Bending	−1	Air	28, 29
BS 5500/API X60	410–490	Burr grinding	Pipe	8.14	Pressure			10
E 355	370	Grinding	T	30	Bending	0.1	Air	2
E 355 KT	410	Grinding	T	40	Bending	0.1	Air	2–38
		Grinding	T	40	Bending	0.1	Sea water	2–38
E 335 R	430	Mild grinding	Butt welded	8	Tension	−1	Air	23
SS 41	256–269	Hammer peening Ø10 $P = 4$ kg/cm^2	Butt welded	13	Tension	0	Air	19
		Hammer peening Ø10 $P = 5$ kg/cm^2	Butt welded	13	Tension	0	Air	19
		Hammer peening Ø8 $P = 4$ kg/cm^2	Butt welded	13	Tension	0	Air	19
		Hammer peening Ø4 $P = 1.5$ kg/cm^2	Butt welded	13	Tension	0	Air	19
		Machining Ø10	Butt welded	13	Tension	0	Air	19
		Grinding Ø180						
			Butt welded	4.5	Tension	−1	Air	50

Appendix 2. Continued on next page

Appendix 2 Part 1: Continued

Material	YS (MPa)	Improvement	Type of joints	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	References
Statoil I	302	Toe grinding	T	30	Bending	0.1	Air	11
		Toe grinding + shot peening	T	30	Bending	0.1	Air	11
		Grind	T	30	3-point bending	0.1	Air	13
		Grind	T	100	Cantilever bending	0.1	Air	13
		Grind	T	160	3-point bending	0.1	Air	13
Superelso 70	685	Disc ground	Cruciform	12.5	Tension	0	Air	3, 6
		Toe burr ground	Cruciform	12.5	Tension	0	Air	3, 6–38
		Fully burr ground	Cruciform	12.5	Tension	0	Air	3, 6
		Hammer peening 4 pass Ø12	Cruciform	12.5	Tension	0	Air	6, 18–38
Ti6A14V titanium		Grinding weld plasma arc	Butt welded	12.7	Tension	$S_m = 250$	A3 sea water synt.	16
		Grinding weld electron beam	Butt welded	12.7	Tension	$S_m = 250$	A3	16

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Appendix 2 Part 2: Improvement technique: TIG (Tungsten Inert Gas)

Type of joint: Butt joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
233	AE235	12	4-point bending	0	Air	Manual	2
						Auto	2
382	HT50A	12.7	Tension	0	Air		25, 46
	HT50B	20	Tension	0	Air		25, 46
385	PN72/484018	12	Tension	−1	Air		23
				−0.5	Air		23
				−0.3	Air	Standard welding	23
						Controlled weld	23
399	AE355	12	4-point bending	0	Air	Manual	2
						Auto	2
		8	Tension	0	Air	Manual	2
550	E490	8	Tension	0.1	Air		13, 14
							3, 28, 36
629	St 51V	15	Tension	0	Air		62
769	St 70V	15	Tension	0	Air		62
				−1	Air		62
824	HT80A	25	Tension	σ_{min}·8	Air	5 kJ/cm	25, 46
						15 kJ/cm	25, 46
						15 kJ/cm + 200°C	25, 46
						25 kJ/cm + 200°C	25, 46
878	St 90V	15	Tension	0	Air		62

Type of joint: Overlap

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
226	S1312	10	Tension	$\sigma_{min} = 14$	Air		34
				$\sigma_{min} = 83$	Air		34
465	DOMEX400	10	Tension	$\sigma_{min} = 14$	Air		34
				$\sigma_{min} = 124$	Air		34
472	HLSA	20	Tension	0.1	Air		53
							22, 53
796	OX802	10	Tension	$\sigma_{min} = 14$	Air		34
				$\sigma_{min} = 235$	Air		34

Appendix 2 Part 2: Continued

Improvement technique TIG (Tungsten Inert Gas)

Type of joint: T joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
302	Statoil	160	3-point bending	0.1	Air		11
340	Statoil	70	Cantilever bending	0.1	Air		11
341	Statoil	100	3-point bending	0.1	Air		11
350	52-3	27	4-point bending	0.1	Air		40
	St 52E	28	4-point bending	0	Air		48
360	SS400	30	3-point bending	0.1	Air	1-pass weld	60
						2-pass weld	60
						1-pass weld root crack	60
						1-pass weld bad condition	60
368	Statoil	30	3-point bending	0.1	Air		11
			4-point bending	0.1	Air		39
409	Fe 510 (BS 4360D)	40	4-point bending	0.1	Air		49, 50
					Sea water		49, 50
490	OX602	30	4-point bending	0.1	Air		40
					Sea water		40
					Sea water + cathode		40
500	E460	40	3-point bending	0.1	Air		20, 41
					Sea water + cathode		20, 41
518	FG47CT	27	4-point bending	0.1	Air		40
540	E460	40	3-point bending	0.1	Air		47
					Sea water + cathode		47
706	E690	8	4-point bending	0.1	Air		54
754	E690	10	4-point bending	0.1	Air		44
			3-point bending	0.1	Air		44
775	E690	10	4-point bending	0.1	Air		15, 44

Type of joint: Longitudinal non-load-carrying joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
628	E560TM	6	Tension	−1	Air	Weld $\phi = 1.6$ mm	35
				$I = 0.99$ AV	Air	Weld $\phi = 1.6$ mm	35
				−1	Air	Weld $\phi = 4$ mm	35
				$I = 0.99$ AV	Air	Weld $\phi = 4$ mm	35

Appendix 2 Part 2: Continued

Improvement techniques: TIG dressing (Tungsten Inert Gas)

Type of joint: Cruciform joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
100	5086H111	6	Tension	0.1	Air	With chamfer	31, 32
						With chamfer	31, 92
250	AS1204	25	Tension	0.3	Air		52
254	AE235	8	Tension	0	Air	Auto	4, 5, 38
						Manual	4, 9, 38
				−1		Auto	4, 9, 38
						Manual	4, 5, 35
345	BS4360-50D	25	Tension	0	Air		16
		38	4-point bending	0	Air		16
372	BS4360-50D	30	Cantilever bending	0	Air		9
					Sea water		9
387	AE355	8	Tension	0	Air	Auto	4, 5, 38
						Manual	4, 9, 38
				−1	Air	Auto	4, 5, 38
						Manual	4, 9, 38
423	SM41B	14	Tension	$\sigma_{min} = 18$	Air		12
					Sea water		12
549	SM58Q	14	Tension	0	Air		37
				$\sigma_{max} = \sigma_y$	Air		37
559	SM58Q	16	Tension	$\sigma_{max} = \sigma_y$	Air	Weld $\phi = 2$ mm	61
						Weld $\phi = 2.6$ mm	61
						Weld $\phi = 3.2$ mm	61
726	HT80C	13	Tension	$\sigma_{min} = 18$	Air		33
764	HT80	30	Cantilever bending	0	Air		9
					Sea water		9
					+ cathode		9
769	St 70V	15	Tension	0	Air		62
775	E690	10	Tension	0.1	Air		15, 44
					With chamfer		44
					With chamfer		44
814	HT80B	16	Tension	$\sigma_{min} = 18$	Air	Auto	25, 46
						$d = 10$ mm	33
						$d = 15$ mm	33
						$d = 5$ mm	33
						$d = 0$ mm	33
						$d = 25$ mm	33
880	KF23M14B	8	Bending	0.1	Air		10

Type of joints: Lap-joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
628	E560TM	6	Tension	−1	Air	1.4 kJ/mm	35
						1 kJ/mm	35
						0.7 kJ/mm	35

Appendix 2 Part 2: Continued

Improvement technique: Shot peening

Type of joint: Butt joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
100	5086H111	5.5	Tension	0.1	Air	Glass ball Ceramic ball Steel ball	31, 32 31, 32 3, 32
430	7075T73	30	Tension	0.1	Air		7
431	7075T6	10	Tension	0.1	Air	Rounded pins Ball	8 8
550	E490	8	Tension	0.1	Air		3, 28, 36
629	St 51V	15	Tension	0	Air		62
769	St 70V	15	Tension	0	Air		62
878	St 90V	15	Tension	0	Air		62
890	E890	50	Tension	0	Air	Ball Mi550 Ball S460	26 26

Type of joint: T joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
368	Statoil	30	4-point bending	0.1	Air		39
460	E460	30	3-point bending	0.1	Air	 20–22 Almen	3, 28, 36 17, 30 27 45
500	E460	40	3-point bending Bending (A.V.)	0.1 −1 −1	Air Sea water + cathode Air Air		20, 41 20, 41 20, 41 20, 41
515	E460	30	3-point bending	0.1	Air		27
540	E460	40	3-point bending	0.1	Air Sea water + cathode		47 0.7
550	E550	20	3-point bending	0.1	Air		45 3, 28, 36
560	E550	20	3-point bending	0.1	Air		17, 30
775	E690	10	3-point bending 4-point bending	0.1 0.1	Air Air		15, 44 15, 44

Type of joint: Longitudinal joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
355	Al-Zn-Mg	9.5	Tension	$\sigma_{min} = 31$	Air		19
262	BS4360-43A	12.5	Tension	0	Air		57, 58
379	Fe510	20	Tension	0.1	Air		55
392	BS4360-50B	20	Tension	0	Air		57, 58
395	Fe510	20	Tension	0.1	Air		56
727	QT445A	20	Tension	0	Air		57, 58
824	RQT700	12.5	Tension	0	Air		57, 58

Appendix 2 Part 2: Continued

Improvement technique: Shot peening

Type of joint: Cruciform joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
100	5086H111	6	Tension	0.1	Air	Without chamfer glass ball	31, 32
						Ceramic ball	31, 32
						Steel ball	31, 32
						With chamfer glass ball	31, 32
						Ceramic ball	31, 32
						Steel ball	31, 32
250	Mild material	—	Tension	0	Air	Weld $\phi = 0.5$–1	51
						0.012–0.016 A	51
						0.016–0.02 A	51
262	BS4360-43A	12.5	Tension	0	Air		57, 58
345	BS4360-50D	38	Cantilever bending	0	Air	0.016–0.02 A	43
						0.024–0.028 A	43
					Sea water		43
					Sea water + cathode		43
360	E36-4	30	Tension	0.1	Air		18
373	BS4360-50B	13	Tension	0	Air	MIG $\phi = 0.6$ 0.012–0.016 A	6
380	BS4360-50B	13	Tension	0	Air	MMA $\phi = 0.8$ 0.012–0.016 A	6
390	BS4360-50B	—	Tension	–1	Air		51
				0	Air		51
				0.5	Air		51
392	BS4360-50B	12.5	Tension	0	Air		57, 58
396	BS4360-50B	13	Tension	0	Air	MMA $\phi = 0.6$ 0.012–0.016 A MMA $\phi = 1$ 0.015–0.019 A	6
397	BS4360-50B	13	Tension	0	Air	MMA $\phi = 0.6$ 0.012–0.016 A MMA $\phi = 0.8$ 0.024–0.028 A	6
400	BS4360-50B	13	Tension	0	Air	MIG $\phi = 0.6$ 0.012–0.016 A	6
						MIG $\phi = 0.8$ 0.012–0.016 A	6
769	St 70V	15	Tension	0	Air		62
775	E690	10	Tension	0.1	Air		15, 44
824	RQT700	13	Tension	0	Air		6

Type of joint: Lap-joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
409	E36	—	4-point bending	0.1	Air		29

Appendix 2 Part 2: Continued

Improvement technique: Combination

Type of joint: Butt joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
430	7075T73	30	Tension	$\sigma_{max} = 200$	Stress release + shot	Flattened sol A3 sol A3	42 42
				0.1	Shot + stress release	2 h to 150°C 4 h to 150°C 60 h to 150°C 4 h to 160°C	7 7 7 7
337	A42FP	8	4-point bending	0.1	TIG + stress release		59
550	E490	8	Tension	0.1	Stress release + grinding + shot		13, 14
629	St 51V	15	Tension	0	TIG + stress release		62
769	St 70V	15	Tension	0	TIG + stress release Shot + stress release TIG + shot		62
878	St 90V	15	Tension	0	TIG + stress release		62
960	TA6V	12.7	Tension	$\sigma_a = 140$	TIG + shot		1

Type of joint: Cruciform joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
360	E36-4	30	Tension	0	Stress release + shot		18
396	BS4360-50B	13	Tension	0	Stress release + shot		6
421	HT60	25	4-point bending	0.1	Stress release + TIG		24
769	St 70V	15	Tension	0	Shot + stress release TIG + stress release TIG + shot		62 62 62

Type of joint: Longitudinal joint

YS (MPa)	Material	Thickness (mm)	Load	$R = \frac{\sigma_{min}}{\sigma_{max}}$	Environment	Conditions	Reference
355	Al-Zn-Mg	9.5	Tension	$\sigma_{min} = 31$	Grinding + shot		19

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Appendix 3

Analysis of results by linear regression in log–log
$\log N = -m \cdot \log \Delta\sigma + \log C$

C: constant
$\Delta\sigma$: for $N = 2 \times 10^6$ cycles

m: slope

Mean curves

Improvement technique: Grinding

			Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
			Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$
$0 < R < 0.1$	Re < 500	Tension	7.16	22.75	198.43	11.22	30.77	151.23	8.37	24.79	161.85	4.28	15.62	149.94
		Bending				3.98	14.71	129.23	4.56	16.44	167.49			
$R = -1$	Re < 500	Tension										6.46	20.96	185.24
		Bending												
$R = 0.3–0.5$	Re < 500	Tension										5.89	18.82	132.77
		Bending												

Improvement technique: TIG dressing

			Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
			Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$
$0 < R < 0.1$	Re < 500	Tension	11.28	34.09	290.36				12.85	37.36	260.54	3.26	13.24	134.96
		Bending	13.87	41.40	338.9	4.76	16.84	162.54	3.98	15.16	167.43			
$R = 1$	Re > 500	Tension	6.22	21.43	269.41				4.58	17.25	245.84			
		Bending				3.65	14.78	208.18	4.86	18	255.79			
$R = -1$	Re < 500	Tension	6.92	43.4	250.5				15.07	44.57	345.78			
		Bending												
	Re > 500	Tension	5.66	19.06	178.87							5.67	18.32	132
		Bending												
$R = 0.3–0.5$	Re < 500	Tension							5.72	18.69	145.98			
		Bending												
$R = 0.3–0.5$	Re < 500	Tension	41.03	106.39	275.11									
		Bending												

Improvement technique: Shot peening

			Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
			Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$	Slope	Constant	$\Delta\sigma$
$0 < R < 0.1$	Re < 500	Tension	92.12	216.09	189.3				10.13	29.64	201.17	4.64	15.95	119.7
		Bending				9.77	29.25	222.31	5.03	17.67	181.39			
	Re > 500	Tension	9.23	29.43	319.83				7.07	23.13	239.38	4.94	17.01	147.29
		Bending				8.26	26.23	258.67						
$R = -1$	Re < 500	Tension							11.64	34.32	255.21			
		Bending				4.91	17.83	223.12						
$R = 0.3–0.5$	Re < 500	Tension							4.77	16.45	132.83			
		Bending												

Improvement technique: Hammer peening

			Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
			Slope	Constant	Δσ	Slope	Constant	Δσ	Slope	Constant	Δσ	Slope	Constant	Δσ
$0 < R < 0.1$	Re < 500	Tension	10.74	31.53	222.85				—	—	—	7.88	24.11	181.74
		Bending							5.88	20.36	245.33			
	Re > 500	Tension										5.68	20.00	258.23
		Bending												
$R = -1$	Re < 500	Tension							5.79	18.88	147.94	9.41	29.83	316.7
		Bending												
$R = 0.3$–0.5	Re < 500	Tension										7.64	22.86	146.55
		Bending												

Appendix 4

Test in air, on joints of thickness $t \leq 25$ mm with load condition (tension or bending) at R between 0 and 0.1

1. Analysis of results by linear regression in log–log.

2. Empirical estimation of inferior envelope curves of the results, in log–log:

$$\log N = -m \cdot \log \Delta\sigma + \log C$$

n: number of failed specimens
m: slope
$\Delta\sigma$: for $N = 2 \times 10^6$ cycles (MPa)
s: estimation of standard deviation (MPa).

Mean curves

Improvement technique: Hammer peening

	Butt joint (A)				T joint (C)				Cruciform (D)				Longitudinal (F)			
	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s
Re < 400	30	10.75	222.9	14.7					19	8.38	239.9	16.4	11	8.16	225.9	7.5
400 < Re < 600													4	2.14	180.3	0.7
Re > 600													4	5.68	258.2	10.7

Improvement technique: Grinding

	Butt joint (A)				T joint (C)				Cruciform (D)				Longitudinal (F)			
	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s
Re < 400	8	7.16	198.4	4.9	18	11.22	151.3	38.3	9	21.7	208	39.2	45	4.77	160.3	29.2
400 < Re < 600									25	5.86	185.2	15.3	7	3.86	109.8	9.5
Re > 600									7	6.94	301.1	11.9				

Improvement technique: TIG dressing

	Butt joint (A)				T joint (C)				Cruciform (D)				Longitudinal (F)			
	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s	n	Slope	Δσ	s
Re < 400		15.6	325.2	58.3	25	3.92	161.6	20.3	48	12.87	260.6	48.3				
400 < Re < 600	156	6.19	268.9	39.5	74	3.34	198.7	42.7	154	4.62	290.2	52				
Re > 600																

Improvement technique: Shot peening

	Butt joint (A)				T joint (C)				Cruciform (D)				Longitudinal (F)			
	n	Slope	Δσ	*s*	*n*	Slope	Δσ	*s*	*n*	Slope	Δσ	*s*	*n*	Slope	Δσ	*s*
Re < 400									66	9.16	194.1	28.0	26	4.64	119.7	14.3
400 < Re < 600	8	14.05	342.5	28.7	30	9.35	277.7	33.7								
Re > 600	99	10.7	330.5	52.7					33	8.78	227.7	39.5	18	4.94	147.3	13.8

Inferior envelope curves

Improvement technique: Hammer peening

	Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
	n	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ
Re < 400	30	6.1	187				19	6.3	215	11	6.9	212
400 < Re < 600												
Re > 600												

Improvement technique: Grinding

	Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
	n	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ
Re < 400	30	7.4	201	18	3.5	73	9	7.7	149	45	4.2	122
400 < Re < 600							25	4.2	139	7	7.7	90
Re > 600							7	5.8	278			

Improvement technique: TIG dressing

	Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
	n	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ
Re < 400	65	5.4	215	25	3.1	129	48	4.1	128			
400 < Re < 600	156	3.9	184	74	3.2	149	154	4.2	252			
Re > 600												

Improvement technique: Shot peening

	Butt joint (A)			T joint (C)			Cruciform (D)			Longitudinal (F)		
	n	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ	*n*	Slope	Δσ
Re < 400							66	4	142	26	3	93
400 < Re < 600	8	5.3	240	30	7.7	236						
Re > 600	99	6	222				33	7.7	173	18	4.4	128